

Symbiodinium spp. associated with scleractinian corals from Dongsha Atoll (Pratas), Taiwan, in the South China Sea

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ABSTRACT

Dongsha Atoll (also known as Pratas) in Taiwan is the northernmost atoll in the South China Sea and a designated marine national park since 2007. The marine park's scope of protection covers the bio-resources of its waters in addition to uplands, so it is important to have data logging information and analyses of marine flora and fauna, including their physiology, ecology, and genetics. As part of this effort, we investigated *Symbiodinium* associations in scleractinian corals from Dongsha Atoll through surveys carried out at two depth ranges (shallow, 1–5 m; and deep, 10–15 m) in 2009 and during a bleaching event in 2010. *Symbiodinium* composition was assessed using restriction fragment length polymorphism (RFLP) of 28S nuclear large subunit ribosomal DNA (nlrDNA). Our results showed that the 796 coral samples from seven families and 20 genera collected in 2009 and 132 coral samples from seven families and 12 genera collected in 2010 were associated with *Symbiodinium* C, D and C+D. Occurrence of clade D in shallow water (24.5%) was higher compared to deep (14.9%). Due to a bleaching event in 2010, up to 80% of coral species associated with *Symbiodinium* C underwent moderate to severe bleaching. Using the fine resolution technique of denaturing gradient gel electrophoresis (DGGE) of internal transcribed spacer 2 (ITS2) in 175 randomly selected coral samples, from 2009 and 2010, eight *Symbiodinium* C types and two *Symbiodinium* D types were detected. This study is the first baseline survey on *Symbiodinium* associations in the corals of Dongsha Atoll in the South China Sea, and it shows the dominance of *Symbiodinium* clade C in the population.

Subjects Ecology, Environmental Sciences, Marine Biology

Keywords *Symbiodinium* association, Dongsha Atoll, *Symbiodinium* C, *Symbiodinium glynii*, South China sea, *Symbiodinium trenchii*

INTRODUCTION

Coral reefs provide habitat for numerous marine organisms and are considered among the richest ecosystems on earth. In addition to their ecological values, they are also economically

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important as they contribute toward food, tourism, coastal protection, aesthetics, and cultural significance to people in coastal areas (Moberg & Folke, 1999; Hoegh-Guldberg, 2004; Wilkinson, 2004) and act as ecosystem engineers (Jones, Lawton & Shachak, 1994; Coleman & Williams, 2002). As a result of climate change and anthropogenic disturbances, corals and coral reefs in the recent decades (30–40 years) have suffered an unprecedented decline in terms of species abundance and community degradation (Hoegh-Guldberg, 1999; Coles & Brown, 2003; Hughes et al., 2003; Bellwood et al., 2004).

Increasing seawater temperature is considered one of the main causes of this decline (Hoegh-Guldberg et al., 2007). Generally, corals undergo a phenomenon known as bleaching when confronted with 1.0–2.0 °C above the mean summer average seawater temperatures. Bleaching is a result of the breakdown of symbiosis between the coral host and single celled algae *Symbiodinium*, either due to release of *Symbiodinium* cells by the host or escape of the cells from the host (see Weis, 2008). While a majority of corals undergo bleaching, some coral species can resist thermal stress or changes in environmental conditions. This is due either to the ability of the coral host to withstand stress or by associating with a more thermally tolerant type of *Symbiodinium*, or to a combination of the two (Berkelmans & Van Oppen, 2006; Bhagooli, Baird & Ralph, 2008; Baird et al., 2009).

Based on various genetic markers (Rowan & Powers, 1991a; Rowan & Powers, 1991b; LaJeunesse, 2001; Van Oppen et al., 2001; Pochon et al., 2001; Fabricius et al., 2004; Coffroth & Santos, 2005; Pochon et al., 2006; Stat et al., 2009), *Symbiodinium* are genetically diverse and has been classified into clades, types and ecomorphs. Different host–symbiont assemblages can respond differently to diverse conditions, such as temperature, irradiance, and sedimentation disturbance. Most *Symbiodinium* clades/types are associated with specific host genera or species (LaJeunesse et al., 2004). In many cases, *Symbiodinium* clades/types associate with only one or a few host species. However, studies also have shown that one of the two partners is more flexible (Baker, 2003a) and occupies defined ecological niches and roles within and across coral hosts (LaJeunesse et al., 2010b; Pochon & Gates, 2010; Weber & Medina, 2012) based on their physiological responses to various environmental stresses (Iglesias-Prieto et al., 2004; Baker, 2003a; Baker, 2003b; Jones et al., 2008; Little, Van Oppen & Willis, 2004; Rowan, 2004; Sampayo et al., 2008; Warner et al., 2006).

Symbiodinium-related stress-resistant mechanisms could be a result of strict association with a stress resistant clade/type of *Symbiodinium* or, in case of coral host with multiple *Symbiodinium* association, the result of shuffling between stress sensitive and stress resistant *Symbiodinium* clades/types. The capacity to shuffle *Symbiodinium* clades/types may be key for their acclimatization and/or adaptation (Baker & Romanski, 2007; Mieog et al., 2007). The general trend is for thermal-tolerant clades/types to supersede thermal-sensitive clades/types under temperature stress (Jones et al., 2008; Jones & Berkelmans, 2010).

As coral and coral reefs face more frequent and intense bleaching events due to climate change and anthropogenic stressors, it is necessary to document the coral-*Symbiodinium* associations from locations which have been ignored or those that are remote. A recent study from western Australia have shown presence of some unique *Symbiodinium* types as well as added to the information on coral-*Symbiodinium* associations and *Symbiodinium*

diversity (Silverstein *et al.*, 2011). Such studies will help us to understand the current status and predict future response of the corals in new and remote locations.

Dongsha Atoll in the South China Sea is one such remote location. Although many studies have been conducted on coral-*Symbiodinium* associations in the South China Sea, no such efforts have been realized in Dongsha Atoll. The Dongsha Atoll Marine National Park was established in 2007 in order to implement legal jurisdiction for conservation efforts. Several studies have been conducted on its reef-building corals despite its remote location. For example, Ma (1937) studied growth rates in different coral species. Coral biodiversity (17 genera and 45 species) was first described by Yang *et al.* (1975), followed by Fang *et al.* (1990), who reported 28 genera and 63 species. Later, Dai, Fan & Wu (1995) recorded 34 genera and 101 species of scleractinian corals, eight genera and 33 species of octocorals, and one genus and three species of hydrocorallina. Recently, and especially after 1998, interest has arisen on the effects of mass coral bleaching of the coral reef community of Dongsha Atoll. After the exceptionally high 1997–98 summer temperatures during an *El Niño–Southern Oscillation* (ENSO) bleaching event, different studies reported a decrease in its coral cover and biodiversity (Fang, 1998; Li & Fang, 2002; Soong, Dai & Lee, 2002). Moreover, Li *et al.* (2000) showed a decline in coral species number due to the extensive use of poisons and explosives from illegal fishing. Before 1998, *Porites* and *Acropora* were the most abundant and widespread genera in Dongsha (Fang *et al.*, 1990; Dai, Fan & Wu, 1995). Although *Porites* has remained a dominant genus from 1998 to the present, it has shared its dominance with other species belonging to the Merulinidae and Fungiidae (Dai, Qin & Zheng, 2013).

Although the species diversity of scleractinian corals at Dongsha has been investigated extensively (Fang *et al.*, 1990; Li *et al.*, 2000; Soong, Dai & Lee, 2002; Dai, Fan & Wu, 1995; Dai, 2005; Dai, 2006; Dai, 2008; Dai, Qin & Zheng, 2013), no studies have been carried out on the coral-*Symbiodinium* associations. Dongsha Atoll is characterized by well-developed tropical atoll reefs with 281 known scleractinian coral species (Dai, Qin & Zheng, 2013). Direct anthropogenic disturbances on the atoll are minimal (about 200 military personnel and park rangers) since Dongsha is a military-exclusive area and a designated marine national park. However, there is occasional human disturbance by fishermen from nearby coastal nations, including China, Philippines, and Vietnam. Hence, the aim of this study was to conduct a baseline survey on *Symbiodinium* associations in the corals of Dongsha Atoll and document the *Symbiodinium* diversity in shallow and deep waters at different sites in the lagoon of the Atoll in 2009 and 2010. In this paper, we report the results from the preliminary survey carried out in the lagoon of Dongsha Atoll on coral-*Symbiodinium* associations.

MATERIALS AND METHODS

Description of the study site and sample collection

Dongsha Atoll (20°35′–47′N and 116°41′–55′E), also known as Pratas Island (Fig. 1), is located in the northern South China Sea, 850 km southwest of Taiwan. Dongsha is a circular atoll about 25 km in diameter and its central lagoon covers more than 600 km².

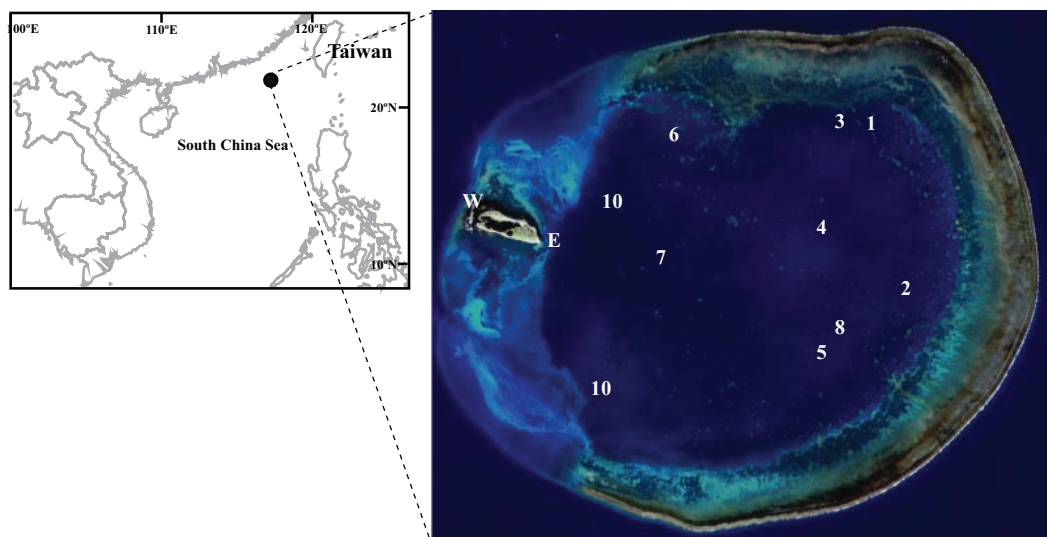


Figure 1 Figure of sampling location. Map of Dongsha Atoll in the South China Sea. Sampling sites in the lagoon are marked 1–10.

Depths in the lagoon range 10–15 m with a maximum depth of 23.7 m (Dai, Qin & Zheng, 2013). Composed of coral debris, Dongsha Island is small (2,860 m long 865 m wide), 2 m above sea level at most, covers a total surface area of 1.74 km², and is located in the western part of the atoll. The circular reef flat around the lagoon spreads over 46 km and its maximum width reaches 2 km.

Coral samples were collected in June and September 2009 and September 2010 in the Dongsha Atoll Lagoon (DAL) (Fig. 1). There was a bleaching episode during summer of 2010 due to elevated seawater temperatures. The corals underwent bleaching mostly in the shallow waters of DAL. Bleached and non-bleached corals were determined by visual survey of color variation between healthy and bleached corals. Sampling was limited to the lagoon due to military-restricted access to the reef crest and outside the atoll. A total of 928 scleractinian coral samples including seven families with 20 and 12 genera in 2009 and 2010 respectively, were collected at two depths: 1–5 m (shallow) and 10–15 m (deep). Samples in 2009 and 2010 were collected from nine and four sites, respectively. Samples (~5–10 cm) from coral colonies were randomly collected by hammer and chisel. All the samples were preserved in 70% ethanol (v/v) and kept at 4 °C until processing. Scleractinian corals were identified to species when possible. Scleractinian taxonomy followed Veron & Stafford-Smith (2000), Dai & Hung (2009a), Dai & Hung (2009b), and Huang et al. (2014). *In situ* seawater temperatures at every site and at both depths were recorded with temperature loggers (HOBO, Pendant™, Onset Computer Corporation, MA, USA) at 30 min intervals (the periods of record were June 17 to September 15, 2009, and May 28 to September 6, 2010).

DNA extraction

Total genomic DNA (coral host + *Symbiodinium*) was extracted by the salting-out method (Ferrara et al., 2006). Coral tissue was lysed overnight in a 2 mL Eppendorf tube with 200

μL of lysis buffer (0.25 M Tris, 0.05 M EDTA at pH 8.0, 2% sodium dodecylsulfate (SDS), and 0.1 M NaCl) and 10 μL of 10 mg mL^{-1} proteinase E at 55 °C in a water bath. NaCl (210 μL at 7 M) was added to the lysed tissue in the tube and the sample mixed carefully by inverting the tube. The solution was then transferred to a 2 mL collection tube containing a DNA spin column (Viogene, Sunnyvale, CA, USA) and centrifuged at 8,000 rpm for 1 min. The lysate was washed twice with 500 μL of ethanol (70%) by centrifuging at 8,000 rpm for 1 min at each step, with an additional centrifugation step at 8,000 rpm for 3 min to dry the spin column. The column was dried further at 37 °C for 15 min and the DNA then eluted by adding 150 μL of distilled water, with a final centrifugation at 14,000 rpm for 3 min. The quality of genomic DNA was checked using a 1% agarose gel and the concentration of eluted DNA was examined using NanoDrop and then stored at -20 °C for further analysis.

Molecular identification of Symbiodinium clades (28S RFLP) and types (ITS2 DGGE)

A total of 928 samples (20 genera in 2009 and 12 genera in 2010) were used to analyze *Symbiodinium* clade composition using RFLP method modified from [Chen et al. \(2005a\)](#) and [Chen et al. \(2005b\)](#). The 5' end of nuclear large subunit ribosomal DNA (nlsrDNA) was amplified using a *Symbiodinium*-specific primer set, 28Szoox-D1/D2F (5'-CCT CAG TAA TGG CGA ATG AAC A-3') and 28Szoox-D1/D2R (5'-CCT TGG TCC GTG TTT CAA GA-3') ([Loh et al., 2001](#)). A 25 μl PCR reaction consisting of 3 μl DNA (10 ng μl^{-1}), 2 μl dNTPs (0.8 mM), 2 μl forward primer (0.16 μM), 2 μl reverse primer (0.16 μM), 3 μl PCR Buffer (1.2X), 0.5 unit *Taq* polymerase (Protech, Taipei, Taiwan), and 12.5 μl distilled water was run on a Px2 thermal cycler (Thermo Scientific, Waltham, MA, USA). The PCR cycling profile consisted of initial denaturation at 95 °C for 1 min followed by 5 cycles of 94 °C for 30 s, 30 cycles of annealing at 55 °C for 1 min and decreasing 1 °C to a final annealing temperatures of 50 °C and 2 min at 72 °C. The final extension was at 72 °C for 10 min. The PCR product was digested with Rsa I (BioLabs, San Diego, CA, USA) solution at 37 °C overnight and then run on 3% agarose gel (2% low melting agarose with 1% agarose) at 50 V for 3 h. Bands were stained using ethidium bromide (EtBr) and visualized under ultraviolet radiation.

For ITS2 *Symbiodinium* type composition, 168 samples were randomly picked from 17 genera in 2009 and 11 genera in 2010. The ribosomal internal transcribed spacer 2 (ITS2) region of *Symbiodinium* was amplified using the primers ITSintfor2, 5'-GAA TTG CAG AAC TCC GTG-3', and ITS2clamp, 5'-CGC CCG CCG CGC CCC GCG CCC GTC CCG CGG GAT CCA TAT GCT TAA GTT CAGCGG GT-3' ([LaJeunesse & Trench, 2000](#)). Each 50 μl polymerase chain reaction (PCR) comprised 50 ng of genomic DNA, PCR buffer, 2.5 mM MgCl_2 , 0.4 mM dNTPs, 0.4 μM of each primer, and 2 units of *Taq* polymerase (Invitrogen, Carlsbad, CA, USA). The PCR was run on a Px2 thermal cycler (Thermo Scientific, Waltham, MA, USA) with a touch-down PCR ([LaJeunesse, 2002](#)) to ensure specificity. An initial denaturation period at 92 °C for 3 min was followed by 20 cycles of 30 s at 92 °C, annealing from 62 °C to a final annealing temperature of 52 °C with decrements of 0.5 °C, and 30 s at 72 °C. Once the annealing temperature reached 52 °C, a further 20 cycles were performed at that annealing temperature, with a final extension period

of 10 min at 72 °C. Each PCR product along with *Symbiodinium* type markers (known ITS2 sequences confirmed by comparing with NCBI GenBank database) was loaded onto an acrylamide denaturing gradient gel (45–80%) and electrophoresed at 115 V for 15 h using a CBS Scientific system (Del Mar, CA, USA). Gels were stained with SYBR Green (Molecular Probes, Eugene, OR, USA) for 15 min and photographed for further analysis. Band patterns were confirmed by sequencing the bands cut from the DGGE gel.

Statistical analysis

Shallow and deep-water temperature comparisons were analyzed by paired *t*-tests and average daily seawater temperature values presented as means \pm standard deviation (SD). The frequency of daily maximum temperature fluctuation at each location and depth was calculated followed by difference in temperature between shallow and deep waters. Finally, the percentage of daily average seawater temperature of over 30 °C during the monitoring period was calculated. The *Symbiodinium* clade values in 2009 and 2010 were converted to percentage within and between genera and within and between two depths. The proportion of *Symbiodinium* clades in coral genera in 2009 and 2010 and between shallow and deep waters was analyzed using a chi-square test. All graphs were drawn using Aabel (Ver. 3.0; Gigawiz Ltd. Co., Tulsa, OK, USA) or Datagraph (Visual Data Tools) software for the Macintosh platform.

RESULTS

Seawater temperature

Seawater temperature was recorded (30 min intervals) from June 17 to September 15, 2009, and May 28 to September 6, 2010 (Figs. 2A and 2B, Data S1–Data S3). During the 2009 period, daily average temperatures at shallow waters (29.55 ± 0.23 °C) were higher than at deep waters (28.82 ± 0.19 °C; Fig. 2A; Table 1; paired *t*-test, $p < 0.001$). Similarly, in 2010, temperatures at shallow waters (29.94 ± 0.29 °C) were higher than at deep waters (29.72 ± 0.32 °C; Fig. 2A; Table 1; paired *t*-test, $p < 0.001$). Overall, ΔT was 0.62 ± 0.3 °C in 2009 and 0.22 ± 0.14 °C in 2010. Daily temperature differences between shallow and deep waters in 2009 were 0.5–1.0 °C and 0–0.5 °C in 2010. In 2009, during the period monitored, 36% of the temperatures (number of days) recorded at the shallow waters exceeded 30.0 °C, whereas only 13% of the temperatures (number of days) recorded at the deep waters reached this value. In 2010, for shallow and deep waters, 61% and 55% of the temperatures (number of days) recorded exceeded 30.0 °C. This was also confirmed by the heat map of seawater temperatures measured at reef base and reef top during June–September and May–September in 2009 and 2010 (Fig. 2B).

In this study, samples were collected from nine locations in the DAL. Since the sampling was random and uneven within and between locations and between two sampling times (2009 and 2010), we present results from 2009 and 2010 by combining the data for locations and depths, rather than discussing the results from individual locations and depths. Hence, we present the overall picture of coral-*Symbiodinium* associations in DAL. Data of *Symbiodinium* clades in coral genera at different locations is provided as Data S4.

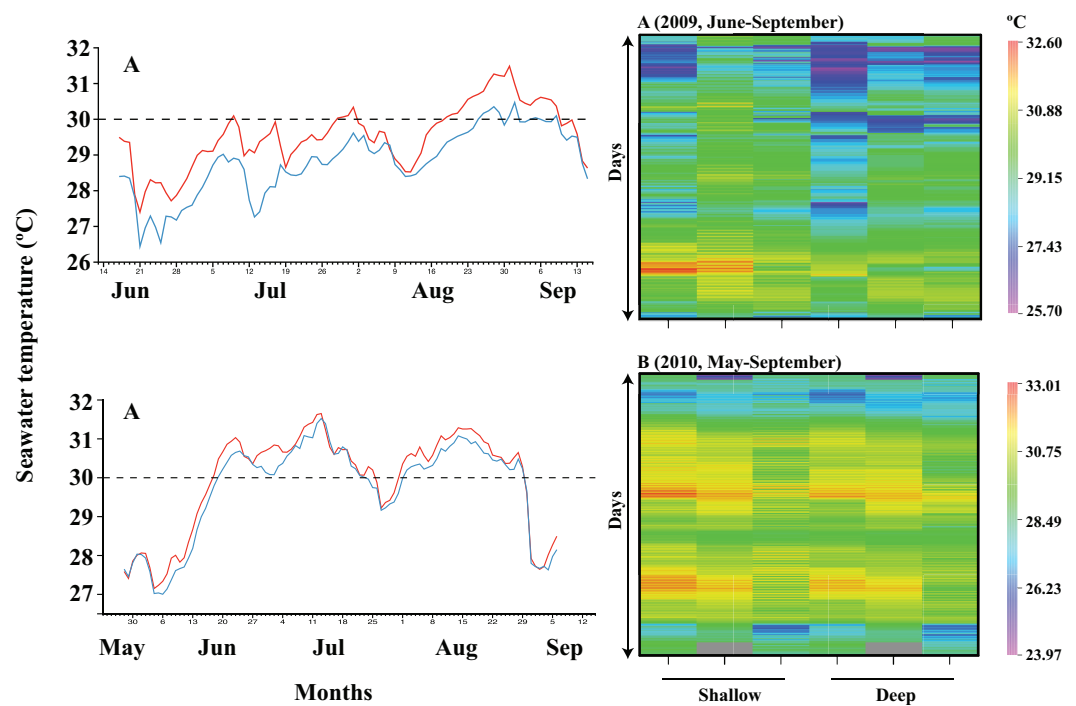


Figure 2 Seawater temperature at the study site in 2009 and 2010. Seawater temperature in 2009: June–September (A); and 2010: May–September (B). The red line represents shallow and the blue line represents deep. Heat map of seawater temperatures measured at reef base and reef top during June–September and May–September in 2009 (A) and 2010 (B), respectively. The y-axis values are seawater temperature recorded at 30 min intervals.

Table 1 Percentage of daily average seawater temperature over 30 °C recorded during the sampling period in 2009 and 2010 within each location.

Temperature over 30 °C	2009	2010
Reef 1 Top		68.10%
Reef 1 Base	7.30%	62.30%
Reef 2 Base	3.20%	
Reef 4 Top		65.50%
Reef 4 Base		64.30%
Reef 5 Top	23.90%	
Reef 5 Base	10.40%	
Reef 6 Top	52.70%	
Reef 6 Base	19.40%	
Reef 9 Top	31.20%	48.80%
Reef 9 Base	23.60%	39.80%
Reef Top over 30 °C	35.90%	60.80%
Reef Base over 30 °C	12.80%	55.50%

Notes.

Top, Shallow; Base, Deep.

***Symbiodinium* clade composition in 2009**

A total of 796 samples from 20 genera and seven families were collected in 2009 (Figs. 3 and 4). RFLP band patterns revealed the presence of *Symbiodinium* clades C, D and C + D.

Symbiodinium Clade C occurred in all 20 genera at shallow and deep waters in 2009. *Leptastrea* (100%), *Fungia* (100%), and *Porites* (100%) were found to harbor only *Symbiodinium* clade C at shallow and deep waters. *Cyphastrea* (100%), *Hydnophora* (100%), *Montipora* (100%), and *Psammocora* (100%) were associated only with *Symbiodinium* clade C at deep waters. At shallow waters, the proportion of *Symbiodinium* clades was 64.18% (clade C), 24.5% (clade D), and 11.34% (clades C + D). And, at deep waters, the proportion of *Symbiodinium* clades was 78.6% (clade C), 14.9% (clade D), and 6.53% (clades C + D). The clade D proportion in comparison to clade C was significantly different at shallow and deep waters (chi-square test, $p = 0.007$). The clade D proportion was high at shallow waters (24.5%) compared to deep waters (14.9%). At both depths, most corals were associated with >50% of *Symbiodinium* clade C, the exceptions being *Oxypora* (33 % in shallow and 44% in deep), *Hydnophora* (22% in shallow), *Echinopora* (9% in shallow and 24% in deep), *Favites* (33% in shallow), *Coelastrea* (37% in shallow), *Astrea* (25% in shallow), *Pectinia* (38% in shallow) and *Goniopora* (43% in shallow), which were associated >50% of the time with clades D or C + D. However, care should be taken when interpreting the results from this data since the sample number was less than ten for most of these genera.

Compared to other genera, Clade D proportions in *Turbinaria* and *Coelastrea* were significantly different when comparing shallow to deep (chi-square test, $p < 0.05$). The clade D proportion of *Turbinaria* at shallow waters (39.5%) was higher than at deep waters (10.8%), and in *Coelastrea* was 46.7% at shallow waters and 15% at deep waters.

***Symbiodinium* clade composition in corals during the 2010 bleaching episode**

A total of 132 samples from 12 genera and seven families were sampled in 2010 from shallow and deep waters (Figs. 3 and 4). *Symbiodinium* clade D showed significant differences (chi-square test, $p < 0.001$) between bleached and non-bleached corals. Clade D proportions were extremely high in non-bleached corals (62.8%) compared to bleached corals (10.9%). Bleached corals were dominated by *Symbiodinium* clade C at each location. *Astreopora*, *Psammocora*, *Fungia*, *Cyphastrea*, *Porites*, and *Oxypora*, all associated with clade C, experienced bleaching in Dongsha Lagoon in the summer of 2010, and *Pavona*, *Coelastrea* and *Echinopora* still experienced bleaching even though they were associated with clades D or C + D.

***Symbiodinium* type composition in corals in 2009 and 2010**

There was no particular trend in the *Symbiodinium* type composition between the two sampling years due to random sampling of the coral colonies (Table 2). However, *Symbiodinium* composition was dominated by different types of *Symbiodinium* C. ITS2 DGGE analysis of DNA samples revealed the presence of eight *Symbiodinium* types (C1, C1b, C3, C15, C21a, C27, C30 and C40; Table 2). C15 was mainly associated with *Montipora* and *Porites*. The composition of *Symbiodinium* type D consisted of only two

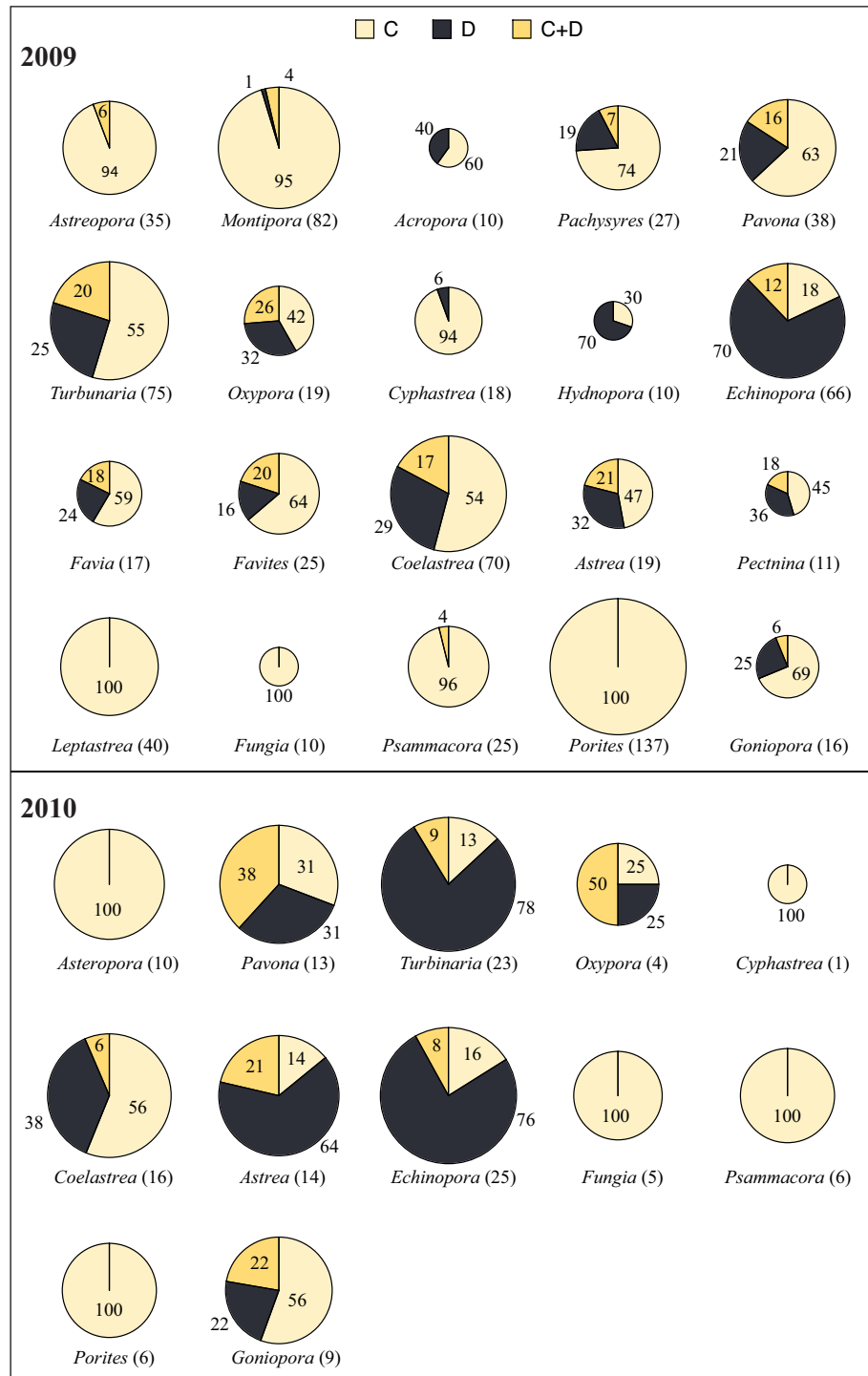


Figure 3 *Symbiodinium* clade distribution corals genera in 2009 and 2010. *Symbiodinium* clade distribution (in percentages) in corals sampled in 2009 (20 genera) and 2010 (12 genera) in Dongha Atoll lagoon. The size of the pie-charts are proportional to the coral sample number. Cream, *Symbiodinium* C; Black, *Symbiodinium* D; and Yellow, *Symbiodinium* D. Sample numbers are indicated in brackets next to each genus name. Numbers inside the pie-charts indicate the percentage of clades.

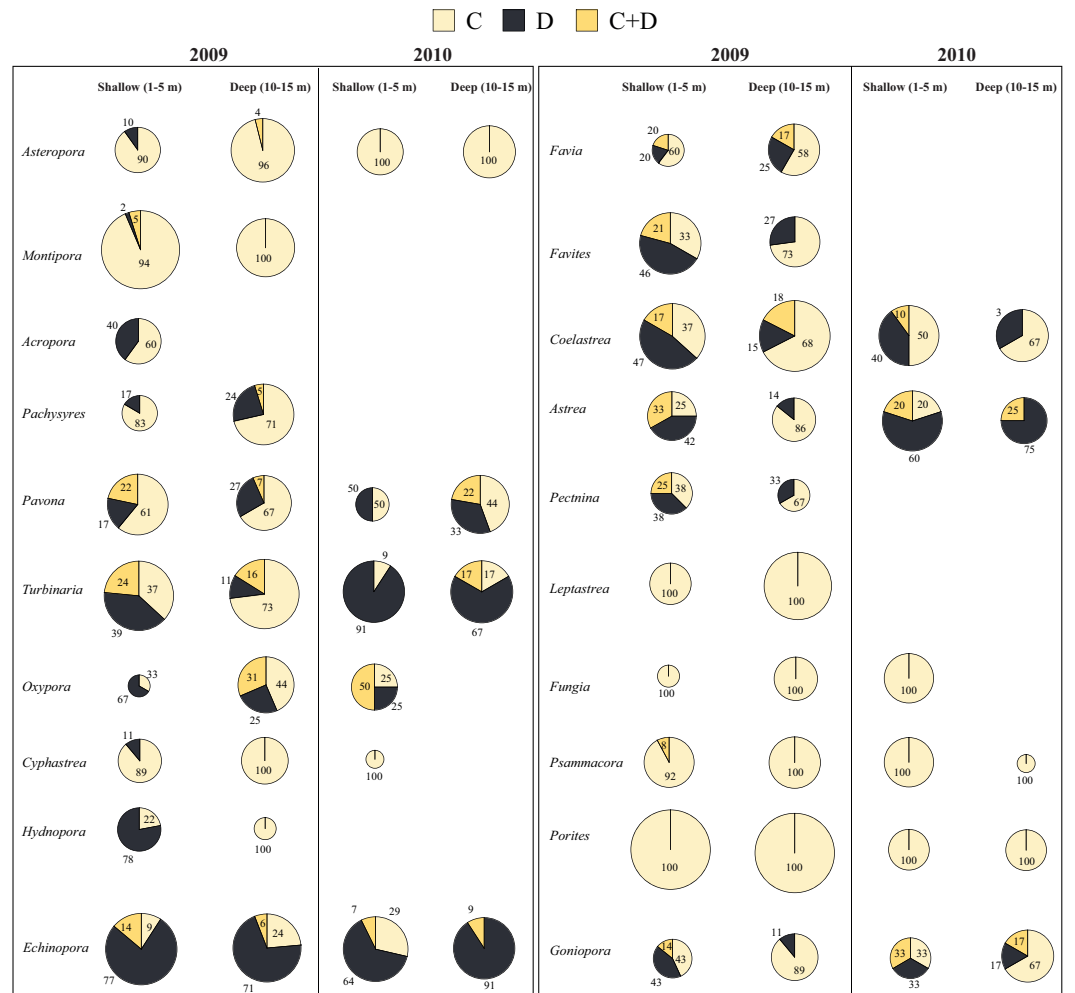


Figure 4 *Symbiodinium* clade distribution in corals at shallow and deep waters in 2009 and 2010. *Symbiodinium* clade distribution in corals at shallow and deep waters in 2009 (20 genera) and 2010 (12 genera) in Dongha Atoll lagoon. The size of the pie-charts are proportional to the coral sample number. Cream, *Symbiodinium* C; Black, *Symbiodinium* D; and Yellow, *Symbiodinium* D. Numbers inside the pie-charts indicate the percentage of clades.

types; *Symbiodinium glynii* (D1) and *Symbiodinium trenchii* (D1a), either separately or in combination, depending on the coral host genus. The two species of *Symbiodinium* D are separated based on a one base-pair difference on a DGGE gel. Because of this fine difference, we ran the gels with appropriate markers for *S. glynii* and *S. trenchii* and also sequenced the cut bands from the ITS2 DGGE gels to reveal the presence of *S. glynii* in several genera of corals sampled from DAL (Fig. S1).

Out of 17 genera analyzed in 2009, the genera *Montipora*, *Acropora*, *Pavona*, *Oxypora*, *Echinopora*, *Favites*, *Astrea*, *Coelastrea*, *Goniopora*, *Hydnopora* and *Pachyseries* were associated with *S. glynii* and/or *S. trenchii* (Table 2). Out of 12 genera analyzed in 2010, the genera *Pavona*, *Turbinaria*, *Oxypora*, *Echinopora*, *Astrea* and *Goniopora* were associated with *S. glynii* and/or *S. trenchii* (Table 2).

Table 2 ITS2 DGGE *Symbiodinium* types in 2009 and 2010.

Genus	2009			2010		
	Depth	Sample number	DGGE	Depth	Sample number	DGGE
<i>Asteropora</i>	3 top	1	C1	3 top	1	C1
	2 base	1	C1	3 base	2	C1
<i>Montipora</i>	2 top	3	C15, D1			
	2 base	1	C15			
	3 top	3	C3, C15			
	3 base	1	C15			
	4 top	2	C15			
	7 top	1	C15			
	8 top	1	C15			
<i>Acropora</i>	10 top	1	C15			
	10 base	5	C15, C30			
<i>Acropora</i>	6 top	4	C1, C3, D1, D1a			
<i>Pavona</i>	2 top	1	C1, C1b, D1	3 top	2	C1b, D1, D1a
	3 top	5	C1b + D1, D1a, C1	3 base	1	C1 + C1b
	3 base	2	C1b	6 base	5	C1, C1b, C27, D1, D1a
	4 top	3	C1, C1b, D1a			
	7 base	1	C1 + C1b			
<i>Turbinaria</i>	10 base	1	C1b			
	2 base	1	C21a	3 top	1	D1 + D1a
	4 base	1	C40	3 base	3	D1 + D1a
	5 base	1	C1	6 base	5	C15, D1 + D1a
<i>Oxypora</i>	6 base	1	C40	10 top	4	C21a, D1 + D1a
	2 base	1	C27	6 top	4	C27, C15, D1 + D1a
<i>Echinopora</i>	10 base	4	D1, D1a, C1			
	2 top	2	D1	3 top	1	D1
	3 top	4	D1, C40, D1a	3 base	2	C27, D1, D1a
	3 base	1	D1a	6 top	4	C40, D1, D1a
	4 top	1	C40 + D1a	6 base	1	D1
	5 base	1	D1a	10 top	1	D1
<i>Favites</i>	10 base	2	C40, D1a			
	2 top	2	D1			
<i>Astrea</i>	3 top	2	D1, D1a			
	2 top	1	D1	3 top	3	D1 + D1a
	6 top	2	D1a	3 base	3	D1 + D1a
<i>Leptastrea</i>	8 top	2	C3, D1a	6 top	2	D1 + D1a
	6 base	1	C1	10 top	1	D1
	10 base	1	C1	3 top	1	C27

(continued on next page)

Table 2 (continued)

Genus	2009			2010		
	Depth	Sample number	DGGE	Depth	Sample number	DGGE
<i>Fungia</i>	2 top	1	C1 + C27	10 top	3	C27
	2 base	1	C27			
	10 top	1	C1			
	10 base	1	C27			
<i>Psammacora</i>	2 top	2	C1, C27	3 base	1	C1
	10 base	1	C1	6 top	2	C27
<i>Porites</i>	2 base	2	C15	3 top	3	C15
	3 top	2	C15	3 base	2	C15
	3 base	1	C15			
	4 base	5	C15			
	10 top	1	C15			
	10 base	1	C15			
<i>Goniopora</i>	3 top	1	D1	3 top	1	D1
	3 base	1	C1	6 base	5	C1, D1
	10 top	1	C1 + D1	10 top	2	C1, D1 + D1a
	10 base	2	C1			
<i>Coelastrea</i>	3 top	2	C1 + D1a			
	3 base	1	C1			
	8 top	1	C15 + D1			
	9 base	1	C21a			
	10 top	1	D1			
	10 base	1	C1 + D1			
<i>Hydnopora</i>	2 top	1	D1			
<i>Pachyseris</i>	6 base	1	C27			
	10 base	1	D1			
Total		102		Total	66	

Notes.

Top, Shallow; Base, Deep.

DISCUSSION

This is the first study to investigate *Symbiodinium* association in the corals of Dongsha Atoll Lagoon (DAL). The main results of this study are that (1) *Symbiodinium* composition in DAL consists of two clades, C and D; (2) eight *Symbiodinium* C types were detected compared to only two *Symbiodinium* D types; and (3) up to 80% of coral species associated with *Symbiodinium* C underwent moderate to severe bleaching in the year 2010. Since we have utilized both RFLP and DGGE for analysis, to avoid confusion, throughout the discussion, clades and types will not be used and instead we will just use either *Symbiodinium* C or *Symbiodinium* D. We also use species name for those *Symbiodinium* types that have been designated formally.

Out of 928 samples collected from 20 (in 2009) and 12 (in 2010) genera of scleractinian corals, 598 hosted *Symbiodinium* C, suggesting its dominance in the South China Sea (see

Table 3 Published reports of *Symbiodinium* clades diversity of scleractinian corals in genus in the West Pacific and South China Sea.

Location	No. of genera analyzed	Clade A	Clade B	Clade C	Clade D	Clade F	Multiple clades	Reference
Penghu Island and Kenting, Taiwan	26	0	0	26	2		6	<i>Chen et al. (2005a)</i>
Dongshan Island, China	3	0	0	3	0		0	<i>Dong et al. (2008a)</i>
Luhuitou fringing reef, China	11	0	0	11	2		2	<i>Dong et al. (2008b)</i>
Xisha Island, China	25	0	0	25	3		3	<i>Dong et al. (2009)</i>
Zhubi coral reef of the Nansha Islands, China	4	0	0	4	1		1	<i>Huang et al. (2006)</i>
Kenting, Taiwan	16			16	13		13	<i>Keshavmurthy et al. (2014)</i>
Dong-Sha Atoll, Taiwan	20	0	0	20	15		14	Present study
Total occurrences of clades	106	1	0	106	36	1	39	

[Table 3](#)). The association of corals with *Symbiodinium* C, in addition to physiological factors, could also be due to seawater temperatures being generally below the bleaching threshold in Dongsha ([Fig. 2](#), [Table 1](#)).

***Symbiodinium* association in corals in 2009**

In 2009, despite *Symbiodinium* C being dominant, it is interesting to highlight the differences seen in *Symbiodinium* D. There was higher proportion (24.5%) in shallow waters compared to deep waters (14.9%). Moreover, the occurrence of *S. glynii* and *S. trenchii* was higher in corals sampled from the shallow waters. The frequency of temperature fluctuations >1 °C at shallow waters was higher than at deep waters, which might be one of the reasons for the higher proportions of *Symbiodinium* D at shallow than at deep waters.

In the present study, *Astreopora*, *Pavona*, *Montipora*, *Psammocora*, *Porites*, *Fungia* and *Leptastrea* showed stable associations with *Symbiodinium* C at shallow and deep waters in DAL, suggesting that either host might be physiologically adjusted to temperature stress or their associated *Symbiodinium* C might have greater photosynthetic stability under thermal stress ([Berkelmans et al., 2004](#); [Thornhill et al., 2006](#); [Van Oppen, Mahiny & Done, 2005](#)). *Turbinaria*, *Oxypora*, *Hydnophora*, *Coelastrea*, and *Favites*, which were dominated by *Symbiodinium* D at shallow compared to deep waters, suggest flexibility in symbiont association in these corals to warmer waters via *Symbiodinium* D. The coral *Echinopora* had a stable and dominant association with *Symbiodinium* D at shallow and deep waters. In the present study, the proportion of *Symbiodinium* D showed a significant difference only in some locations, which might be due to difference distribution of coral host associated with *Symbiodinium* D.

***Symbiodinium* association in corals in 2010 during a bleaching event**

In 2010, scleractinian corals at Dongsha suffered from high seawater temperature stress caused by a La Niña event. *Astreopora*, *Cyphastrea*, *Fungia*, *Psammocora* associated with clade C including the genus *Porites*, which is generally considered as stress resistant (associated with *Symbiodinium* C15) experienced bleaching. Moreover, coral genera *Pavona*, *Coelastrea*, *Echinopora*, which were associated with clade C or C + D, also

experienced bleaching. Bleaching was seen in 84% of corals associated with clade C compared to only 10.87% of corals associated with clade D. Bleaching in those corals associated with clade D could be due to seawater temperature above threshold limits during the summer of 2010. In a previous study, the critical coral bleaching temperature threshold at Dongsha was determined to be 29.6 °C (Dai, 2008). During May 28 to September 6, 2010, average temperatures at shallow waters (29.9 °C) and deep waters (29.7 °C) within DAL exceeded the critical value and may have induced coral bleaching (Fig. 2, Table 1). Consistent above 30 °C seawater temperature for more than a week, both in shallow and deep waters, could have resulted in extensive bleaching in corals in 2010 (Fig. 2, Table 1). As a result of random and uneven sampling, it is not possible to analyze the correlation between *Symbiodinium* clades and seawater temperature results. We suggest that future studies in DAL should focus on obtaining samples from tagged coral colonies in different seasons and depths to understand the dynamics of coral-*Symbiodinium* associations.

***Symbiodinium* type composition in corals in 2009 and 2010**

From ITS2 DGGE analysis, DAL corals were found to be associated with eight *Symbiodinium* C (*Symbiodinium* *goreau* (C1), C1b, C3, C15, C21a, C27, C30 and C40) and this number is greater than in the corals at Kenting, southern Taiwan (Keshavmurthy et al., 2014). Conversely, only two *Symbiodinium* D types were observed: *Symbiodinium* *glynii* (D1) and *Symbiodinium* *trenchii* (D1a). The presence of *Symbiodinium* D in corals sampled in 2010 was more obvious, and we believe this might have been due to the influence of seawater temperature (Fig. 2, Table 1). Our results also showed that *S. glynii* was dominant in many coral genera, both in 2009 (12 genera out of 20) and 2010 (seven genera out of 12), indicating that *S. glynii* may not be specific to any particular host species (LaJeunesse, 2002; Baker, 2003a; Baker, 2003b). This is the first work to show the presence of *S. glynii* in such a large number of coral genera and hence, we believe that *S. glynii* may not be as specific or rare, as previously thought (see LaJeunesse et al., 2010a).

CONCLUSIONS

The present study has shown that *Symbiodinium* C is dominant at Dongsha Atoll in the South China Sea corals and that natural stressors, such as elevated seawater temperatures, can influence *Symbiodinium* associations in Dongsha Atoll corals. The baseline information provided on the composition of *Symbiodinium* in corals from Dongsha Atoll through the present work will help carrying out comprehensive and detailed studies on the diversity of *Symbiodinium* in corals over time. By analyzing data from normal and coral-bleaching years, we have shown that the composition of *Symbiodinium* in some corals is different between years in remote and undisturbed locations such as Dongsha Atoll. Such studies are important for understanding the future responses of corals to climate change in remote atolls. With increasing threats to coral health, mainly from temperature-induced bleaching events as seen in the Great Barrier Reef in 2016, studies documenting the *Symbiodinium* associations in corals of Dongsha Atoll will help to educate and inform park managers of Dongsha Atoll Marine National Park managers about appropriate management and conservation measures. The focus on the status of coral reefs in the South China Sea,

including Dongsha Atolls, has gained attention in the past couple of years, particularly due to the recent destruction via land-filling of several reefs several atolls in the South China Sea. Although offshore atoll reefs in the South China Sea are found to be in better condition than near-shore reefs (Hughes, Huang & Young, 2013), they can still undergo bleaching and mortality as a result of climate change (Graham et al., 2006) and other stressors (Hughes, Huang & Young, 2013). Trans boundary cooperation in the South China Sea region has become important for the maintenance and conservation of the various atolls and islands in the South China Sea (McManus, 2010). As part of the conservation program in Dongsha Atoll, it is necessary to combine the influence of natural disturbances and the effects of anthropogenic stressors, such as fishing activities, in order to understand the alterations of the present and their influences on future coral communities.

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ADDITIONAL INFORMATION AND DECLARATIONS

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Shashank Keshavmurthy conceived and designed the experiments, performed the experiments, analyzed the data, wrote the paper, prepared figures and/or tables, reviewed drafts of the paper.
- Kuo-Hsun Tang and Chia-Min Hsu performed the experiments, analyzed the data, prepared figures and/or tables.
- Chai-Hsia Gan performed the experiments.
- Chao-Yang Kuo conceived and designed the experiments, performed the experiments.
- Keryea Soong contributed reagents/materials/analysis tools, logistics towards coral sampling at Dongsha.

- Hong-Nong Chou contributed reagents/materials/analysis tools.
- Chaolun Allen Chen conceived and designed the experiments, contributed reagents/materials/analysis tools, wrote the paper, reviewed drafts of the paper.

Data Availability

The following information was supplied regarding data availability:

The raw data has been supplied as [Supplementary Files](#).

Supplemental Information

Supplemental information for this article can be found online at <http://dx.doi.org/10.7717/peerj.2871#supplemental-information>.

REFERENCES

- Baird AH, Bhagooli R, Ralph P, Takahashi S. 2009.** Coral bleaching: the role of the host. *Trends Ecology and Evolution* **24**:16–20 DOI [10.1016/j.tree.2008.09.005](https://doi.org/10.1016/j.tree.2008.09.005).
- Baker AC. 2003a.** Flexibility and specificity in coral-algal symbiosis: diversity, ecology, and biogeography of *Symbiodinium*. *Annual Review of Ecology and Systematics* **34**:661–689 DOI [10.1146/annurev.ecolsys.34.011802.132417](https://doi.org/10.1146/annurev.ecolsys.34.011802.132417).
- Baker AC. 2003b.** Symbiont diversity on coral reefs and its relationship to bleaching resistance and resilience. In: Rosenberg E, Loya Y, eds. *Coral health and disease*. Berlin: Springer, 177–191.
- Baker AC, Romanski AM. 2007.** Multiple symbiotic partnership are common in scleractinian corals, but not in octocorals: comment on Goulet(2006). *Marine Ecology Progress Series* **335**:237–242 DOI [10.3354/meps335237](https://doi.org/10.3354/meps335237).
- Bellwood DR, Hughes TP, Folke C, Nystrom M. 2004.** Confronting the coral reef crisis. *Nature* **429**:827–833 DOI [10.1038/nature02691](https://doi.org/10.1038/nature02691).
- Berkelmans R, De'ath G, Kininmonth S, Skirving WJ. 2004.** A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns and predictions. *Coral Reefs* **23**(1):74–83 DOI [10.1007/s00338-003-0353-y](https://doi.org/10.1007/s00338-003-0353-y).
- Berkelmans R, Van Oppen MJH. 2006.** The role of zooxanthellae in the thermal tolerance of corals: a 'nugget of hope' for coral reefs in an era of climate change. *Proceedings of the Royal Society B: Biological Sciences* **273**:2305–2312 DOI [10.1098/rspb.2006.3567](https://doi.org/10.1098/rspb.2006.3567).
- Bhagooli R, Baird AH, Ralph PJ. 2008.** Does the coral host protect its algal symbionts from heat and light stresses? *Proceedings of the Eleventh International Coral Reef Symposium* **5**:113–117.
- Chen CA, Wang JT, Fang LS, Yang YW. 2005b.** Fluctuating algal symbiont communities in *Acropora palifera* (Cnidaria; Scleractinia) from Taiwan. *Marine Ecology Progress Series* **295**:113–121 DOI [10.3354/meps295113](https://doi.org/10.3354/meps295113).
- Chen CA, Yang YW, Wei NV, Tsai WS, Fang LS. 2005a.** Symbiont diversity in scleractinian corals from tropical reeds and subtropical non-reed communities in Taiwan. *Coral Reefs* **24**(1):11–22 DOI [10.1007/s00338-004-0389-7](https://doi.org/10.1007/s00338-004-0389-7).

- Coffroth MA, Santos SR. 2005.** Genetic diversity of symbiotic dinoflagellates in the genus *Symbiodinium*. *Protist* **156**(1):19–34 DOI [10.1016/j.protis.2005.02.004](https://doi.org/10.1016/j.protis.2005.02.004).
- Coleman FC, Williams SL. 2002.** Overexploiting marine ecosystem engineers: potential consequences for biodiversity. *Trends Ecology and Evolution* **17**(1):40–44 DOI [10.1016/S0169-5347\(01\)02330-8](https://doi.org/10.1016/S0169-5347(01)02330-8).
- Coles SL, Brown BE. 2003.** Coral bleaching—capacity for acclimatization and adaptation. *Advances in Marine Biology* **46**:183–223 DOI [10.1016/S0065-2881\(03\)46004-5](https://doi.org/10.1016/S0065-2881(03)46004-5).
- Dai CF. 2005.** The corals reefs ecological resources of sea area of Dongsha are investigated and monitored. Construction and Planning Administration Ministry of Interior Request Report Chapter 4: 1–31 (in Chinese with English abstract).
- Dai CF. 2006.** The corals reefs ecological resources of sea area of Dongsha are investigated and monitored. Construction and Planning Administration Ministry of Interior Request Report Chapter 4: 67–137 (in Chinese with English abstract).
- Dai CF. 2008.** The corals reefs ecological resources of sea area of Dongsha are investigated and monitored. Construction and Planning Administration Ministry of Interior Request Report Chapter 4: 51–108 (in Chinese with English abstract).
- Dai CF, Fan TY, Wu CS. 1995.** Coral fauna of Tungsha Tao (Pratas Island). *Acta Oceanographica Taiwanica* **34**:1–16.
- Dai CF, Hung S. 2009a.** *Scleractinia of Taiwan I. The complex group*. Taipei: National Taiwan University, 172 p.
- Dai CF, Hung S. 2009b.** *Scleractinia of Taiwan II. The robust group*. Taipei: National Taiwan University, 162 p.
- Dai CF, Qin XY, Zheng AY. 2013.** *Coral fauna of Dongsha Atoll in the South China Sea (In Chinese)*. Kaohsiung: National Marine Park Headquarters, 344 pp.
- Dong ZJ, Huang H, Huang LM, Li YC. 2009.** Diversity of symbiotic algae of the genus *Symbiodinium* in scleractinian corals of the Xisha Island in the South China Sea. *Journal of Systematics and Evolution* **47**(4):321–326 DOI [10.1111/j.1759-6831.2009.00034.x](https://doi.org/10.1111/j.1759-6831.2009.00034.x).
- Dong ZJ, Huang H, Huang LM, Li YC, Li XB. 2008a.** PCR-RFLP analysis of large subunit rDNA of symbiotic dinoflagellates in scleractinian corals from Luhuitou fringing reef of Sanya, Hainan. *Biodiversity Science* **16**:498–502 (in Chinese with English abstract) DOI [10.3724/SP.J.1003.2008.08074](https://doi.org/10.3724/SP.J.1003.2008.08074).
- Dong ZJ, Huang H, Huang LM, Li YC, Zhou GW. 2008b.** Molecular taxonomy and diversity of symbiotic dinoflagellates in scleractinian corals near the sea off the Dongshan Island in Fujian Province. *Journal of Oceanography in Taiwan Strait* **27**:135–140 (in Chinese with English abstract).
- Fabricius KE, Mieog JC, Colin PL, Idip D, Van Oppen MJH. 2004.** Identity and diversity of coral endosymbionts (zooxanthellae) from three Palauan reefs with contrasting bleaching, temperature and shading histories. *Molecular Ecology* **13**(8):2445–2458 DOI [10.1111/j.1365-294X.2004.02230.x](https://doi.org/10.1111/j.1365-294X.2004.02230.x).
- Fang LS. 1998.** The status of marine ecology in Dong-Sha Atoll. In: *European-Asian workshop on investigation and management of Mediterranean and South China Sea Coastal Zone*. Nov 9–11 1998, Hong Kong.

- Fang LS, Shao KT, Liu L, Li JJ. 1990. *A survey of the marine ecological resources of Dong-Sha Atoll*. Taiwan: Fishery Management Department, Kaohsiung City government 61 pp(in Chinese with English abstract).
- Ferrara GB, Murgia B, Parodi AM, Valisano L, Cerrano C, Palmisano G, Bavestrello G, Sara M. 2006. The assessment of DNA from marine organisms via a modified salting-out protocol. *Cellular and Molecular Biology Letters* 11:155–160 DOI 10.2478/s11658-006-0013-7.
- Graham NAJ, Wilson SK, Jennings S, Polunin NVC, Bijoux JP, Robinson J. 2006. Dynamic fragility of oceanic coral reef ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* 103(22):8425–8429 DOI 10.1073/pnas.0600693103.
- Hoegh-Guldberg O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50(8):839–866 DOI 10.1071/MF99078.
- Hoegh-Guldberg O. 2004. Coral reefs in a century of rapid environmental change. *Symbiosis* 37:1–31.
- Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318(5857):1737–1742 DOI 10.1126/science.1152509.
- Huang D, Benzoni F, Fukami H, Knowlton N, Smith N, Budd A. 2014. Taxonomic classification of the reef coral families Merulinidae, Montastraeidae, and Diploastraeidae (Cnidaria: Anthozoa: Scleractinia). *Zoological Journal of the Linnean Society* 171(2):277–355 DOI 10.1111/zoj.12140.
- Huang H, Dong ZJ, Huang LM, Zhang JB. 2006. Restriction fragment length polymorphism analysis of large subunit rDNA of symbiotic dinoflagellates from scleractinian corals in the Zhubi Coral Reef of the Nansha Islands. *Journal of Integrative Plant Biology* 48(2):148–152 DOI 10.1111/j.1744-7909.2006.00148.x.
- Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nystrom M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* 301(5635):929–933 DOI 10.1126/science.1085046.
- Hughes TP, Huang H, Young MAL. 2013. The wicked problem of China's disappearing coral reefs. *Conservation Biology* 27:261–269 DOI 10.1111/j.1523-1739.2012.01957.x.
- Iglesias-Prieto R, Beltran VH, LaJeunesse TC, Reyes-Bonilla H, Thome PE. 2004. Different algal symbionts explain the vertical distribution of dominant reef corals in the eastern Pacific. *Proceedings of the Royal Society B: Biological Sciences* 271:1757–1763 DOI 10.1098/rspb.2004.2757.
- Jones AM, Berkelmans R. 2010. Potential costs of acclimatization to a warmer climate: growth of a reef coral with heat tolerant vs. sensitive symbiont types. *PLOS ONE* 5:e10437 DOI 10.1371/journal.pone.0010437.

- Jones AM, Berkelmans R, Van Oppen MJH, Mieog JC, Sinclair W. 2008.** A community change in the algal endosymbionts of a scleractinian coral following a natural bleaching event: field evidence of acclimatization. *Proceedings of the Royal Society B: Biological Sciences* **275**:1359–1365 DOI [10.1098/rspb.2008.0069](https://doi.org/10.1098/rspb.2008.0069).
- Jones CG, Lawton JH, Shachak M. 1994.** Organisms as ecosystem engineers. *Oikos* **69**:373–386 DOI [10.2307/3545850](https://doi.org/10.2307/3545850).
- Keshavmurthy S, Meng P-J, Wang J-T, Kuo C-Y, Yang S-Y, Hsu C-M, Gan C-H, Dai C-F, Chen CA. 2014.** Can resistant coral-*Symbiodinium* associations enable coral communities to survive climate change? A study of a site exposed to long-term hot water input. *PeerJ* **2**:e327 DOI [10.7717/peerj.327](https://doi.org/10.7717/peerj.327).
- LaJeunesse TC. 2001.** Investigating the biodiversity, ecology, and phylogeny of endosymbiotic dinoflagellates in the genus *Symbiodinium* using the internal transcribed spacer region: in search of a “species” level marker. *Journal of Phycology* **37**:866–880 DOI [10.1046/j.1529-8817.2001.01031.x](https://doi.org/10.1046/j.1529-8817.2001.01031.x).
- LaJeunesse TC. 2002.** Diversity and community structure of symbiotic dinoflagellates from Caribbean coral reefs. *Marine Biology* **141**(2):387–400 DOI [10.1007/s00227-002-0829-2](https://doi.org/10.1007/s00227-002-0829-2).
- LaJeunesse TC, Bhagooli R, Hidaka M, deVantier L, Done T, Schmidt GW, Fitt WK, Hoegh-Guldberg O. 2004.** Closely related *Symbiodinium* spp. differs in relative dominance in coral reef host communities across environmental, latitudinal and biogeographic gradients. *Marine Ecology Progress Series* **284**:147–161.
- LaJeunesse TC, Pettay DT, Sampayo EE, Phongsuwan N, Brown BE, Obura DO, Hoegh-Guldberg O, Fitt WK. 2010b.** Long-standing environmental conditions, geographic isolation and host-symbiont specificity influence the relative ecological dominance and genetic diversification of coral endosymbionts in the genus *Symbiodinium*. *Journal of Biogeography* **37**(5):785–800 DOI [10.1111/j.1365-2699.2010.02273.x](https://doi.org/10.1111/j.1365-2699.2010.02273.x).
- LaJeunesse TC, Smith R, Walther M, Pinson J, Pettay DT, McGinley M, Aschaffenburg M, Medina-Rosas P, Cupul-Magna AL, Perez AL, Reyes-Bonilla H, Warner M. 2010a.** Host-symbiont recombination versus natural selection in the response of coral-dinoflagellate symbioses to environmental disturbance. *Proceedings of the Royal Society B: Biological Sciences* **277**:2925–2934 DOI [10.1098/rspb.2010.0385](https://doi.org/10.1098/rspb.2010.0385).
- LaJeunesse TC, Trench RK. 2000.** The biogeography of two species of *Symbiodinium* (Freudenthal) inhabiting the intertidal anemone, *Anthopleura elegantissima* (Brandt). *Biological Bulletin* **199**(2):126–134 DOI [10.2307/1542872](https://doi.org/10.2307/1542872).
- Li JJ, Fang LS. 2002.** The management of Dong-Sha Atoll as an effective marine protected area. In: *Proceedings of the fourth Conference on the Protected Areas of East Asia (IUCN/WCPA/EA-4)*, Taipei, 403–415.
- Li JJ, Lee TF, Tew KS, Fang LS. 2000.** Changes in the coral community at Dong-Sha Atoll, South China Sea from 1975 to 1998. *Acta Zoologica Taiwanica* **11**(1):1–15.
- Little AF, Van Oppen MJH, Willis BL. 2004.** Flexibility in algal endosymbioses shapes growth in reef corals. *Science* **304**(5676):1492–1494 DOI [10.1126/science.1095733](https://doi.org/10.1126/science.1095733).

- Loh WKW, Loi T, Carter D, Hoegh-Guldberg O. 2001.** Genetic variability of the symbiotic dinoflagellates from the wide ranging coral species *Seriatopora hystrix* and *Acropora longicyathus* in the Indo-West Pacific. *Marine Ecology Progress Series* **222**:97–107 DOI [10.3354/meps222097](https://doi.org/10.3354/meps222097).
- Ma TYH. 1937.** On the growth of reef corals and its relation to the sea water temperature. *National Institute of Zoology and Botany (Academia Sinica) Zoology* **1**:1–226.
- McManus J. 2010.** Towards establishing a Spartly Islands international marine peace park: ecological importance and supportive collaborative activities with an emphasis on the role of Taiwan. *Ocean Development & International Law* **41**(3):270–280 DOI [10.1080/00908320.2010.499303](https://doi.org/10.1080/00908320.2010.499303).
- Mieog JC, Van Oppen MJH, Cantin NE, Stam WT, Olson JL. 2007.** Real-time PCR reveals a high incidence of Symbiodinium clade D at low levels in four scleractinian corals across the Great Barrier Reef: implications for symbiont shuffling. *Coral Reefs* **26**(3):449–457 DOI [10.1007/s00338-007-0244-8](https://doi.org/10.1007/s00338-007-0244-8).
- Moberg F, Folke C. 1999.** Ecological goods and services of coral reef ecosystems. *Ecological Economics* **29**:215–233 DOI [10.1016/S0921-8009\(99\)00009-9](https://doi.org/10.1016/S0921-8009(99)00009-9).
- Pochon X, Gates RD. 2010.** A new *Symbiodinium* clade (Dinophyceae) from soritid foraminifera in Hawaii. *Molecular Phylogenetics and Evolution* **56**:492–497 DOI [10.1016/j.ympev.2010.03.040](https://doi.org/10.1016/j.ympev.2010.03.040).
- Pochon X, Montoya-Burgos JI, Stadelmann B, Pawloski J. 2006.** Molecular phylogeny, evolutionary rates, and divergence timing of the symbiotic dinoflagellates genus *Symbiodinium*. *Phylogenetics and Evolution* **38**:20–30 DOI [10.1016/j.ympev.2005.04.028](https://doi.org/10.1016/j.ympev.2005.04.028).
- Pochon X, Pawloski J, Zaninetti L, Rowan R. 2001.** High genetic diversity and relative specificity among *Symbiodinium*—like endosymbiotic dinoflagellates in soritid foraminiferans. *Marine Biology* **139**:1067–1078 DOI [10.1007/s002270100674](https://doi.org/10.1007/s002270100674).
- Rowan R. 2004.** Thermal adaptation in reef coral symbionts. *Nature* **430**:742 DOI [10.1038/430742a](https://doi.org/10.1038/430742a).
- Rowan R, Powers DA. 1991a.** A molecular genetic classification of zooxanthellae and the evolution of animal-algal symbioses. *Science* **251**(4999):1348–1351 DOI [10.1126/science.251.4999.1348](https://doi.org/10.1126/science.251.4999.1348).
- Rowan R, Powers DA. 1991b.** Molecular genetic identification of symbiotic dinoflagellates (zooxanthellae). *Marine Ecology Progress Series* **71**:65–73 DOI [10.3354/meps071065](https://doi.org/10.3354/meps071065).
- Sampayo EM, Ridgeway T, Bongaerts P, Hoegh-Guldberg O. 2008.** Bleaching susceptibility and mortality of corals are determined by fine-scale differences in symbiont type. *Proceedings of National Academy of Sciences of the United States of America of the United States of America* **105**:10444–10449 DOI [10.1073/pnas.0708049105](https://doi.org/10.1073/pnas.0708049105).
- Silverstein RN, Correa A, Lajeunesse TC, Baker AC. 2011.** Novel algal symbiont (*Symbiodinium* spp.) diversity in reef corals of Western Australia. *Marine Ecology Progress Series* **422**:63–75 DOI [10.3354/meps08934](https://doi.org/10.3354/meps08934).
- Soong K, Dai CF, Lee CP. 2002.** Status of Pratas Atoll in South China Sea. In: *Proceedings of the 4th conference on the protected areas of East Asia (IUCN/WCPA/EA-4)*, Taipei, 739–742.

- Stat M, Loh W, Hoegh-Guldberg O, Carter DA. 2009.** Stability of coral-endosymbiont associations during and after a thermal stress event in the southern Great Barrier Reef. *Coral Reefs* **28**(3):709–713 DOI [10.1007/s00338-009-0509-5](https://doi.org/10.1007/s00338-009-0509-5).
- Thornhill D, LaJeunesse TC, Kemp DW, Fitt WK, Schmidt GW. 2006.** Multi-year, seasonal genotypic surveys of coral-algal symbioses reveal prevalent stability or post-bleaching reversion. *Marine Biology* **148**(4):711–722 DOI [10.1007/s00227-005-0114-2](https://doi.org/10.1007/s00227-005-0114-2).
- Van Oppen MJH, Mahiny A, Done T. 2005.** Geographic distribution of zooxanthellae types in three coral species on the Great Barrier Reef sampled after the 2002 bleaching event. *Coral Reefs* **24**(3):482–487 DOI [10.1007/s00338-005-0487-1](https://doi.org/10.1007/s00338-005-0487-1).
- Van Oppen MJH, Palstra FP, Piqet AMT, Miller DJ. 2001.** Patterns of oral-dinoflagellate associations in *Acropora*: significance of local availability and physiology of *Symbiodinium* strains and host-symbiont selectivity. *Proceedings of the Royal Society B: Biological Sciences* **268**:1759–1767 DOI [10.1098/rspb.2001.1733](https://doi.org/10.1098/rspb.2001.1733).
- Veron JEN, Stafford-Smith M. 2000.** *Coral Reefs of the World*. Townsville: Australian Institute of Marine Science.
- Warner ME, LaJeunesse TC, Robison JD, Thur RM. 2006.** The ecological distribution and comparative photobiology of symbiotic dinoflagellates from reef corals in Belize: potential implications for coral bleaching. *Limnology and Oceanography* **51**(4):1887–1897 DOI [10.4319/lo.2006.51.4.1887](https://doi.org/10.4319/lo.2006.51.4.1887).
- Weber M, Medina M. 2012.** The role of microalgal symbionts (*Symbiodinium*) in holobiont physiology. *Advances in Botanical Research* **64**:119–140 DOI [10.1016/B978-0-12-391499-6.00004-9](https://doi.org/10.1016/B978-0-12-391499-6.00004-9).
- Weis VM. 2008.** Cellular mechanisms of Cnidarian bleaching: stress causes the collapse of symbiosis. *The Journal of Experimental Biology* **211**:3059–3066 DOI [10.1242/jeb.009597](https://doi.org/10.1242/jeb.009597).
- Wilkinson C. 2004.** *Status of coral reefs of the world*. Townsville: Australian Institute of Marine Science.
- Yang RT, Huang CC, Lee CS, Tsai HJ, Sun CL. 1975.** *Report on a survey at Dongsha Island and the adjacent area. Special Publication No. 8*, Taipei: Institute of Oceanography, National Taiwan University, 15.